

MODERN SIGNAL PROCESSING TECHNIQUE FOR OPTIMAL SIGNAL TO NOISE RATIOS

By

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Phase sensitive detection provides the theoretically optimum technique for the recovery of signal intensity information from noise. Application of this technique to signal processing problems encountered in typical experiments in physics, chemistry, astronomy and biology is discussed.

It is probably a safe statement to make that the majority of present day research in the physical sciences involves the measurement of small effect phenomena where noise sets the limit to attainable precision or detectability. In noise one includes all disturbing elements over which the experimentalist has no control, such as effects produced by the fundamental thermal fluctuations of all matter not at absolute zero, or by statistical fluctuations due to the quantized nature of light, electrical currents, etc. Also in noise one groups such extraneous disturbances as building vibrations, variations in room temperature and stray electrical signal pickup; disturbances which in principle can be reduced to an arbitrarily small value but which in practice are difficult to remove entirely from the picture.

The experimentalist who has pursued a phenomenon of interest down to the noise threshold is continually alert for methods that may improve the signal-to-noise ratio (S/N) of his measurements. Such a method is the lock-in technique, which in many cases can improve experimental S/N by 40 db or more.

Since World War II, signal processing techniques that approach attainment of the theoretically optimum signal-to-noise ratio have been developed. Some of these techniques were applied in those spectacular experiments in which radar signals reflected from Venus and the moon were detected. While these experiments were very complex, involving the use of high speed digital computers to recover the desired information from noise, the underlying principles are relatively simple and can easily be applied to more mundane research measurements. A few experimentalists have in fact been using these techniques for some time, but there are still many researchers who do not yet realize the power they provide in improving S/N .

A factor that has worked against the general application of the lock-in technique has been the absence of a commercially-available "black box" that would make it unnecessary for the individual experimentalist to design his own lock-in detection system. The recent introduction of commercially available general purpose lock-in amplifiers should facilitate the introduction of this powerful technique into many research and devel-

opment laboratories, and should be particularly helpful to those individuals who are skilled in a particular scientific discipline but who are not especially familiar with electronic information processing.

Let us now consider the principles of small-effect measurement and see how S/N may be optimized. We shall be concerned here with those cases in which the quantities to be detected or measured can be made to appear as electrical signals. Fortunately most physical quantities can in fact be converted to electrical signals by suitable transducers, such as photoelectric cells, strain gages, microphones, bolometers, etc. A hypothetical experiment in which a small effect physical quantity $Q(t)$, is to be measured as it changes with time is shown in Figure 1 in block diagram form. For example it may be a very weak source of light from a variable star or from phosphorescent bacteria, but the technique is general and can be made to apply to almost any measurement. The S/N one obtains in a given system is determined by the nature of the signal and noise sources and by the properties of the various components of the system, in particular the bandwidths employed.

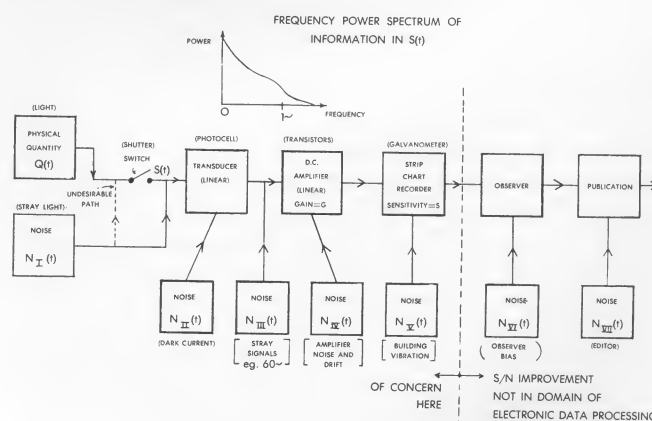


FIG. 1 Hypothetical experiment to measure and record the small-effect physical quantity $Q(t)$ as it changes with time. Various source of noise are shown. Also shown is the frequency power spectrum of $S(t)$.

In the traditional way of carrying out such a measurement the system might consist of a linear transducer that converts the quantity being measured into a D.C. electrical signal which is then amplified by an amplifier with D.C. response and recorded on a strip chart recorder. An important part of the system is the switch S which is opened periodically to observe system zero drift. It is very necessary to insure that the switch interrupts *only* the quantity being measured and not some of the noise sources. A typical recording from such a set-up might look like Figure 2. Here, an attempt has been made to draw in smooth curves to represent "true" zero and signal. The S/N in this example is somewhat greater than unity at the start of the recording but becomes less than one toward the end.

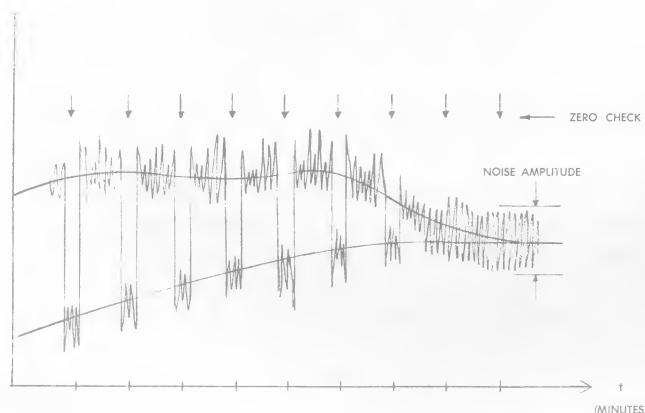


FIG. 2. Hypothetical record from experiment of Fig. 1.

Now what are the S/N considerations? The unknown is a slowly varying function of time, $Q(t)$, which is periodically interrupted (made zero). The transducer converts this into a corresponding electrical signal. We may speak of the frequency power spectra of the quantities $Q(t)$, or $E(t)$ (with their periodic interruptions). These are found simply by determining the Fourier components of the input signals. The signal power in the example under study is to be found in a small band around zero frequency. Now the bandwidth of the amplifier in this system should be chosen to match this signal spectrum, i.e., it should have a corresponding bandwidth about zero frequency. The resulting S/N will then be determined by the ratio of signal power to noise power within this bandwidth. All the sources of noise in front of, and in, the amplifier must be considered. Of course the response of the recorder to sources of noise after amplification is independent of the amplifier characteristics.

Unfortunately for S/N considerations in this example, the choice of a band about zero frequency as the

location for the signal power is a singularly bad one, for conventional power amplifying devices have noise power spectra that vary as the reciprocal of frequency near zero frequency (see Figure 3) due to the so-called flicker effect. Attempting to improve S/N by reducing bandwidth here is futile.

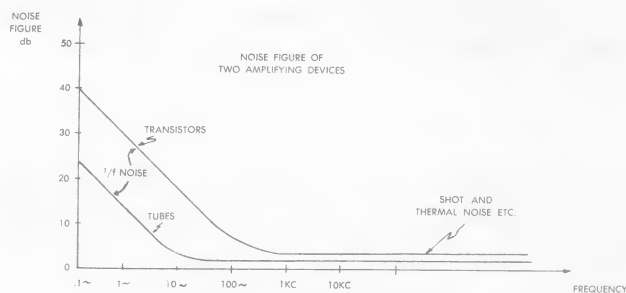


FIG. 3 Representative noise figures of two amplifying devices, the vacuum tube and the transistor, showing the characteristic $1/f$ increase at low frequencies.

To avoid the region of $1/f$ noise the signal information should be made to appear at some frequency, f_0 , above 100 cps for tube amplifiers and above 1 kc for transistor systems. It may be desirable to go to even higher values if the signal source $Q(t)$ has high frequency components associated with it (i.e. is rapidly varying). It may be necessary to go to lower frequencies if other necessary components in the system do not have a high enough frequency response. The signal power may be made to appear at any arbitrary frequency f_0 by opening and closing the switch S (in Figure 1) at that frequency. In reality one would use a mechanical chopper, sector disc light chopper, or arrange in some way to have the desired quantity $Q(t)$ modulated at f_0 by the application of an electric current, magnetic field, or mechanical stress of that frequency (or at one half f_0 for quadratic effects). The rest of the system must now be made compatible with the fact that the signal power is now contained in a band about f_0 and its multiples, the bandwidth being determined by the high frequency cut-off of the Fourier spectrum of $Q(t)$. (Actually most of the signal power is to be found in the band about the fundamental, f_0 , and harmonics can generally be neglected.) First, the transducer employed to convert $Q(t)$ into $E(t)$ must be capable of responding to f_0 . Second, the amplifier of gain G employed to boost signal power need only respond to the narrow band about f_0 containing the signal power. Finally, we must convert the amplified signal power $G \cdot E(t)$ into a D.C. current of magnitude proportional to the amplitude of the signal, and record this detected signal on a strip chart recorder. The S/N achievable with a system of this type is dependent

only on the bandwidth of the amplifier-detector employed and on the nature of the noise sources.

A hypothetical experiment in which this philosophy of information handling is used is shown in Figure 4. Here the problem is to measure the weak phosphorescence induced in a sample by exciting radiation over a wide range of wave-lengths. We shall now consider this experiment in detail from the standpoint of optimum S/N.

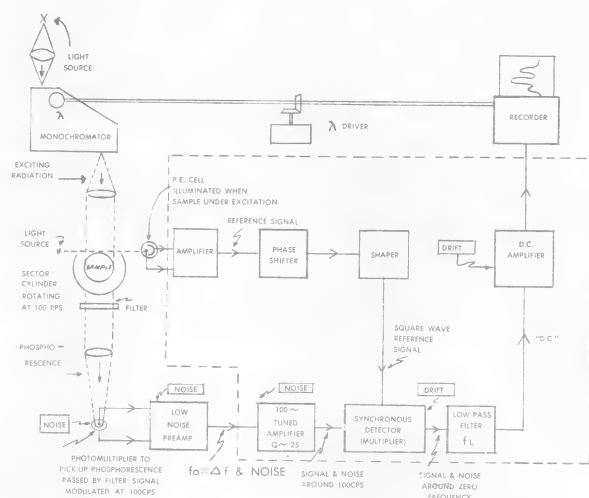


FIG. 4 Hypothetical experiment to determine the exciting radiation wave length dependence of the weak phosphorescence of a sample. Here lock-in signal processing techniques are used. Components enclosed in dotted area make up a Lock-In Amplifier.

1) A trivial observation is that the signal should be made as large as possible by using as high intensity an exciting source as possible and that the collection efficiency (f-number) of the optics should be maximized.

2) Stray light—particularly stray light that may be modulated at 100 cps by the rotating shutter system—should be strenuously avoided. Thus it is obvious that the modulation should be performed in such a way that ideally only the light due to the phosphorescence of the sample is modulated. Steady light on the detector (photomultiplier), while not contributing to signal, will increase the noise because the noise contribution due to all D.C. components of the photomultiplier current increases as the square root of that current (shot effect).

3) A photomultiplier should be used that has good quantum efficiency at the wave length under study (again large signal) and a good noise figure (low dark current, leakage, etc). As much gain as possible should be taken in the photomultiplier because, in general, the amplification obtained in the secondary emission process is about optimum from the noise standpoint. If a pre-amp is needed to follow the photomultiplier, the signal level from the latter should be made many times the inherent noise of the pream-

plifier, if at all possible.

The information at this point is contained in the 100 cps electrical signal from the photomultiplier and preamplifier. Actually the information is in a narrow band about the frequency $f_0 = 100$ cps if the quantity being measured shows any variation with time (as it will in our hypothetical system because of the changing excitation wave length). The noise in the channel will consist of 60 and 120 cycle pick-up from the power lines, broad band noise from the shot effect in the detector and preamplifier, flicker-effect noise from the amplifier, microphonic pick-up, etc. There remains the problem of picking the 100 cps signal out of all this noise and measuring and recording its magnitude. Continuing our consideration of S/N:

4) The 100 cps signal must now be brought to a level sufficiently high to drive the detector that will convert the information to D.C. This level should be such that the inherent drift in the detector and following D.C. amplifier are of negligible magnitude compared to the D.C. signal. In general this amplification is best done in a tuned amplifier of moderate Q. While not contributing to the overall system S/N, the tuned amplifier helps prevent overloading of the detector by random noise (through reducing the bandwidth of the noise at the detector input) or by spurious signals (e.g. 60 and 120 cps pick up).

5) The detection of the 100 cps signal is the most critical part of the system from the standpoint of S/N. The detector should have as narrow a bandwidth as possible consistent with the fact that bandwidth sets limits on the rapidity with which the amplitude of the initial unknown signal may be allowed to change and also sets limits on the observation time required to make the measurement. In going to a very narrow bandwidth detector, provision must be made to prevent the center frequency of the detector from drifting off f_0 . Fortunately the lock-in detector, or synchronous detector as it is sometimes called, is available for this application. The bandwidth can be made as narrow as desired in a simple way (by increasing an RC time constant) and the center frequency is "locked-in" to the carrier frequency, f_0 , avoiding drift problems. The synchronous detector is essentially a mixer that multiplies the unknown signal, $f_0 \pm \Delta f$, by the "reference signal", a pure square wave signal at exactly f_0 which is phase related in a definite way to the unknown signal. This mixing results in the unknown information appearing in a band of frequencies $\pm \Delta f$ about zero frequency (D.C.). (The upper side band at $2 f_0$ is of no interest here and is stopped by the low pass filter which follows the detector). The reference signal is obtained in a way that makes it unambiguous in frequency and phase with respect to the signal modulation wave-form. The bandwidth of the detector may be made arbitrarily narrow by passing the "zero

frequency" output through a RC low pass filter. The effective bandwidth of the detector will then be $f=1/2RC$ cycles.

5) The D.C. output of the detector must now be brought up to a level that will drive stripchart recorders. Any drift in the output of the detector or D.C. amplifier will be another source of "noise" in the experiment.

Figure 5 shows in diagrammatic form the handling of the information in our hypothetical experiment. It shows the original information at D.C., the moving of the signal to $f_0=100$ cps, amplification, and finally demodulation and filtering.

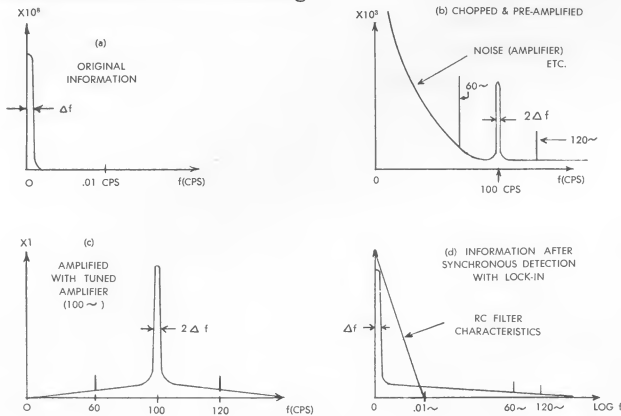


FIG. 5 "Spectra" showing how information signal is handled in hypothetical experiment of Fig. 4. By moving original information at D.C. to 100 cps, it is possible to amplify with the introduction of a minimum amount of noise.

It should be noted that, apart from D.C. drift in the synchronous detector and following amplifier, the

system should be free from drift. Because of the interrupting action at the light chopper there is effectively a "zero" taken 100 times a second. However, any pick-up of 100 cps signals in the system will result in an "offset" of the output. This may be checked for by removing the sample. In practice the drift in the detector and D.C. amplifier can easily be made negligibly small.

Commercial lock-in amplifiers¹ which have the essential components of a complete signal processing system have recently become available. These employ the techniques that have been discussed above and allow the experimentalist to achieve essentially optimum S/N in his measurements. Accompanying Figures 6 and 7 show the block diagram and front panel of one such unit. (The Model JB-5 Lock-In Amplifier manufactured by Princeton Applied Research Corporation, Princeton, New Jersey) These units are very flexible in their

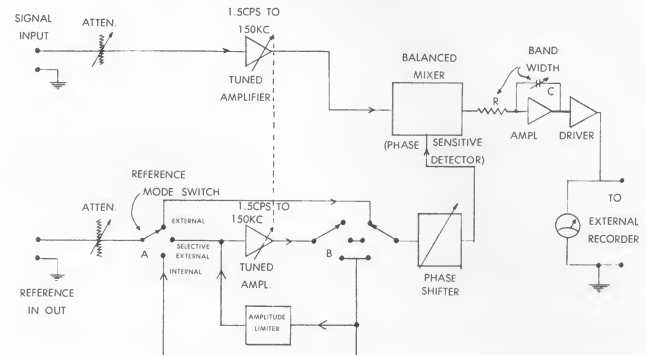


FIG. 6 Block diagram of complete signal processing unit lock-in amplifier Model JB-5.



FIG. 7 Model JB-5 lock-in amplifier.

¹ R.D. Moore, Electronics, June 8, 1962

application and, in general, only require being connected to a suitable transducer and to a recorder to achieve a complete signal processing system. The unit shown has a built-in oscillator and can thus produce a reference signal which is used internally for demodulation and is available externally for use as the source of the modulation for the unknown signal.

Figure 8 shows how the commercial lock-in might be used in an experiment in biology. The experiment is purely imaginary but is fairly representative of what might be done. It illustrates the method in which the signal to be measured is generated in response to a reference voltage that is produced in the lock-in unit itself.

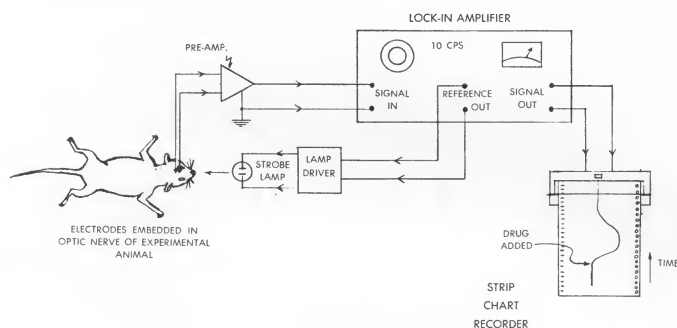


FIG. 8 Hypothetical experiment to test the effect of drug on the strength of the optical signal induced in experimental animal by 10 cps flashing light.

The strobe light is made to flash at a 10 cps rate in synchronism with the 10 cps signal from the lock-in unit. This flashing light induces 10 cycle signals in the optic nerve of the experimental animal which is picked-up by embedded electrodes. The faint electrical signals are preamplified, fed to the lock-in unit where they are further amplified by an amplifier tuned to 10 cps, detected in a synchronous detector, filtered, and recorded. The action of drugs on this signal may be studied by observing the amplitude of the recorded signal.

A classic example of the use of the lock-in signal processing technique is that of the Dicke Radiometer.² With this radiometer Dicke was able to measure the radiation temperature of the sky, sun, moon, and terrestrial objects to high precision. A block diagram of such a radiometer is shown in Figure 9.

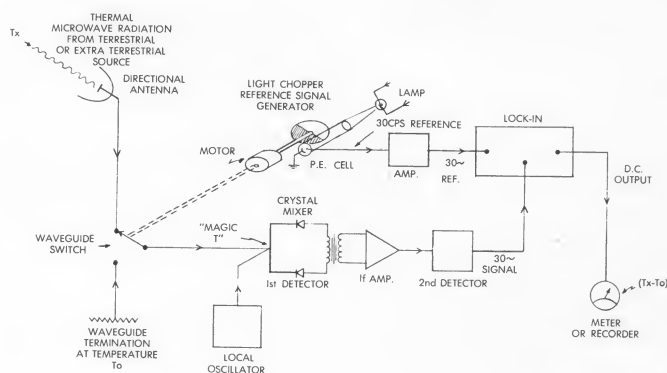


FIG. 9 Radiometer of the Dicke type.

In the foregoing, the lock-in amplifier technique has been discussed in terms of its operating principles, and a few examples of applications have been given. The applications of this technique are, in general, limited only by the ingenuity of the experimenter. In many cases a commercially available lock-in amplifier can be added to an existing piece of apparatus with good and sometimes even spectacular results. This will be particularly true if the existing apparatus makes use of D.C. detection methods. However in order to make the best possible use of this technique it is generally necessary to design the whole experiment around it. Such questions as the best method of modulation (what to modulate and how), the type of transducer to be used, the optimum operating frequency and many more must be considered with great care. In order to answer these questions correctly the experimenter must be equipped with an understanding of the lock-in amplifier technique as well as of the nature and behavior of the various factors that introduce noise, and that finally form the fundamental limitations of his experiment. The experimenter who makes the effort to acquire a sound understanding of these factors will be rewarded by a broadening of his research horizons and by a clearer insight into the scope of his experimental techniques.

² R.H. Dicke, Rev. Sci. Inst. 17, 268 (1947)

NOTES

LOW-NOISE AMPLIFIERS

MODELS CR-4 AND CR-4A

LOW-NOISE, HIGH-GAIN AMPLIFIERS

FEATURING

- DIFFERENTIAL/SINGLE-ENDED INPUT
- EXTREMELY LOW NOISE
- HIGH/LOW INPUT IMPEDANCE
- BATTERY OPERATION
- SELECTABLE BANDPASS
- HIGH RELIABILITY
- 20-80 DB GAIN
- COMPLETELY TRANSISTORIZED
- PANEL MOUNTING



The PAR Models CR-4 and CR-4A are extremely low-noise amplifiers, ideally suited to many small signal processing applications requiring a high quality pre-amplifier. In addition, these amplifiers can be used to greatly extend the low-level signal recovery capability of PAR Lock-In Amplifiers.

These units can be powered from their own internal battery (either long-life mercury cells or a rechargeable nickel-cadmium battery pack) or operated from the AC line (applicable only to those units with rechargeable packs).

Low-noise operation is obtained as follows: The units utilize separate input stages for the high and low input impedance mode of operation. The low impedance, differential input stage, having a voltage gain-of-10, utilizes bipolar transistors in a circuit which insures that transistor operating voltages and currents are held within a range providing optimum noise performance. When high input impedance is selected, high impedance, unity-voltage-gain buffer amplifiers, which utilize unipolar P-channel silicon field-effect transistors (again operating at carefully selected voltages and currents), are inserted prior to each of the inputs of the above mentioned voltage gain-of-10 amplifier. Precautions to minimize noise are also taken in the following amplifier stage after which only minimal noise precautions are required in succeeding amplifier stages. The high impedance, single-ended input position provides the optimum noise performance due to the elimination of a noise source (as compared to the differential input).

The Model AM-1 Input Transformer is available for use with the basic amplifiers, and will be highly useful in experiments involving low source impedance (less than 100 ohms). When used in this manner, low source impedances are essentially transformed to a higher level where improved noise performance can be achieved.

The Low-Noise Amplifier will find use by itself and with Lock-In Amplifiers in the following experimental applications: radio astronomy, nuclear and electron resonance experiments, experiments in special and general relativity, optical pumping, infrared studies, laser investigations, electrophysiological signal processing, radiometers, plasma studies, vibrating sample magnetometers, electronic polarizing microscopes, electroencephalographic studies, mass spectrometers, and in many other small signal recovery problems.

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SPECIFICATIONS — LOW-NOISE AMPLIFIER MODELS CR-4 AND CR-4A

INPUT MODES (selectable by front panel switch):

LOW - Z (DIFFERENTIAL): Input impedance of 50K ohms minimum. Optimum mode for resistive sources to 10K ohms.

HI - Z (DIFFERENTIAL): Input impedance of 50 megohms minimum shunted by less than 10 picofarads (either input to ground). Optimum mode for resistive sources from 10K to 20 megohms.

* **HI - Z (SINGLE-ENDED):** Input impedance of 50 megohms minimum shunted by less than 10 picofarads.

* While any differential input can be operated single-ended by simply connecting one of the inputs to the common terminal, the circuitry comprising the single-ended and differential high impedance input is actually different. The "HI - Z (SINGLE-ENDED)" mode will be the optimum mode of operation for high (greater than 10K) resistive source impedances of an inherently single-ended nature while still retaining the ability to eliminate extraneous signals due to ground currents. In addition, for source impedances of 100K ohms or less, this mode will yield noise figures approaching 3 db better than would be obtained in the "HI - Z (DIFFERENTIAL)" mode due to the elimination of a noise source (as compared to the differential input mode).

COMMON MODE REJECTION: 60 db minimum (measured at 1KC).

GAIN: 20-80 db (10-10,000) $\pm$ 1 db in 20 db (decade) increments.

GAIN STABILITY: Over the recommended range of temperature and battery voltage, the nominal gain will be maintained within $\pm$ 1 db.

LINEARITY: For input signals below the maximum allowable levels specified, the gain will be linear within $\pm$ 1%.

OUTPUT IMPEDANCE: Less than 100 ohms.

FREQUENCY RESPONSE: Selectable high and low frequency roll-off characteristics. Frequency roll-off settings on front panel are 6 db positions and attenuation increases at a 12 db/octave rate. Calibration accuracy of 6 db points is $\pm$ 10% of frequency.

MODEL CR-4

LOW FREQUENCY ROLL-OFFS: Front panel switch settings at 1, 3, 10, 30, 100 and 300 cps; 1, 3, 10, 30 and 100 KC.

HIGH FREQUENCY ROLL-OFFS: Front panel switch settings at 3, 10, 30, 100 and 300 cps; 1, 3, 10, 30, 100 and 300 KC.

MODEL CR-4A

LOW FREQUENCY ROLL-OFFS: Same as MODEL CR-4 except lowest possible setting is 10 cps.

HIGH FREQUENCY ROLL-OFFS: Same as MODEL CR-4 except lowest possible setting is 30 cps.

RECOVERY TIME: The ability of the amplifier to return to its nominal operating condition after the application of a 1000:1 overload signal is as follows:

MODEL CR-4

Recovery Time: 30 seconds (nominal) (Overload signal applied for 1 minute.)

Recovery Time: 15 seconds (nominal) (Overload signal applied momentarily.)

MODEL CR-4A

Recovery Time: 3 seconds (nominal) (Overload signal applied for 1 minute.)

Recovery Time: 1.5 seconds (nominal) (Overload signal applied momentarily.)

NOISE: See noise figure contours and measurement method given on following pages. These curves represent the effects of source impedances.

PRICES/ORDERING INFORMATION:

CR-4 or CR-4A without batteries	\$575.00
CR-4 or CR-4A with Mercury Pack	600.00
CR-4 or CR-4A with Rechargeable Battery Pack	645.00
CR-4 or CR-4A with both Battery Packs supplied	680.00
Mercury Battery Pack	35.00
Rechargeable Battery Pack	80.00
Rack (for mounting one or two units in standard 5 1/4" panel)	25.00
Transformer AM-1 (supplied with 3-foot cable and mating connectors)	135.00
EXPORT PRICES APPROXIMATELY 5% HIGHER (EXCEPT CANADA).	

WARRANTY: One year.

pedance and frequency on attainable noise figure for a typical production unit. The following are "cardinal points" for "LOW - Z" and "HI - Z" modes of operation and can be considered as "check points" for all units.

LOW - Z: Measured at a frequency of 10 KC with a 2 K ohm resistive source impedance, the noise figure is less than 3 db.

HIGH - Z: Measured at a frequency of 10 KC with a 200 K ohm resistive source impedance, the noise figure is less than 3 db.

In addition, for those desiring noise data referred to a shorted input, the following represents maximum values for the LOW IMPEDANCE POSITION with shorted input and measured from 10 cps to the indicated high frequency roll-off setting.

HIGH FREQ. ROLL-OFF	RMS NOISE VOLTAGE
100 CPS	0.06 μ V
1 KC	0.15 μ V
10 KC	0.3 μ V
100 KC	0.9 μ V

MAXIMUM SIGNAL LEVEL: Output signal is limited by output stage to 5 volts peak-to-peak (minimum) into a 10 K ohm load. At low gain settings, maximum input signal is limited by input stage to 40 millivolts peak-to-peak.

The voltage (D.C. + peak A.C.) applied to the input terminals should not exceed $\pm$ 4 volts.

POWER REQUIREMENTS:

Due to complete use of solid-state devices, the power required is 12 volts at approximately 19 ma. The user has the following choice of power sources, either one of which is internal to the unit and interchangeable with the other.

1. Nickel-Cadmium Rechargeable Battery Pack with self-contained recharging circuit allows approximately 24 hours of continuous isolated operation before battery requires recharging. At expense of possible 60 cycle pickup, amplifier can be operated during battery recharging cycle. Power required is 105-125 VAC or 210-250 VAC; 50 or 60 cps.
2. Disposable Long-Life Mercury Battery Pack having a capacity of 14,000 ma-hours and giving approximately 750 hours continuous operation.

A battery test circuit applicable to either power source allows for testing of battery condition.

TEMPERATURE RANGE: 10°C to 45°C.

DIMENSIONS:

6 1/2 inches wide; 5 inches high; 8 3/4 inches deep. One or two units can be mounted in 5 1/4" standard rack panel without requiring modifications or any additional hardware.

WEIGHT: CR-4 or CR-4A with Mercury Battery Pack: 9.5 lbs.

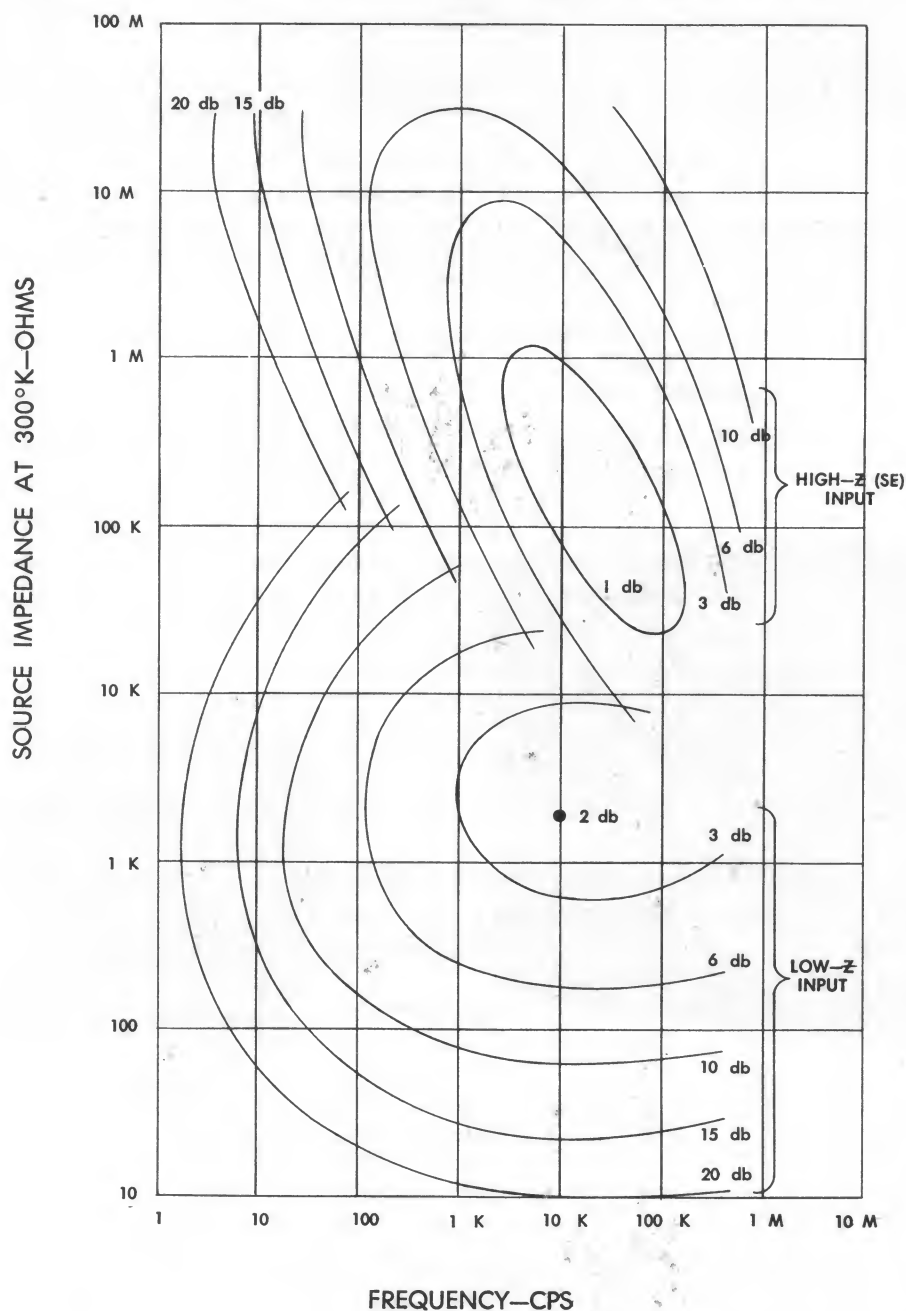
CR-4 or CR-4A with Rechargeable Battery Pack: 8.5 lbs.

ACCESSORIES: Princeton Applied Research Model AM-1 Input Transformer.

It can be seen from the noise figure contours that noise figure is considerably degraded at impedance levels less than 100 ohms. The Model AM-1, when used in conjunction with the basic amplifier unit in the "HI - Z (DIFF.)" position, essentially transforms the low impedance to a level where improved noise performance can be achieved. The turns ratio of the Model AM-1 is approximately 100:1 and, with a 10 ohm source resistance, has a 3 db bandwidth extending from 10 cps to 15 KC. See the noise figure contours (for source impedances of 1 to 1000 ohms) of the basic amplifier unit when used in conjunction with the Model AM-1 Input Transformer.

Specifications and Prices are subject to change without notice.

TYPICAL AMPLIFIER NOISE FIGURE CONTOURS



NOISE FIGURE is a common method of rating a unit and is defined as follows:

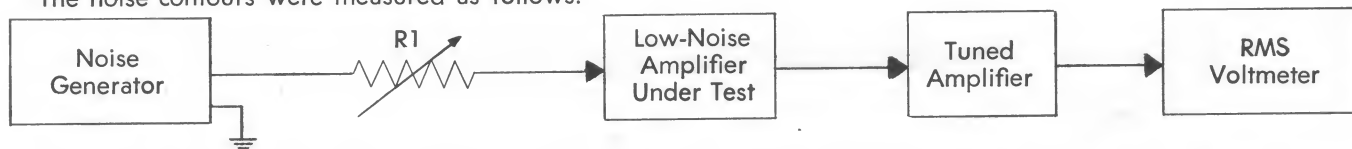
$$\text{Noise Figure (F)} = 20 \log_{10} \frac{(\text{Signal-to-Noise Voltage Ratio at Input})}{(\text{Signal-to-Noise Voltage Ratio at Output})} \text{ DB}$$

The above equation assumes that operation is confined to the linear region of the unit under test.

The noise figure contours are essentially the loci of points of constant noise figure as a function of source impedance and operating frequency. They allow the user to determine the optimum points of operation as well as indicating regions of source impedance and operating frequency where it is not desirable to operate.

Generally speaking, it can be seen from the contours that at a given operating frequency and input impedance position (Hi or Lo-Z), the noise figure is degraded as the source impedance is reduced. When experiments involve source impedance of the order of 100 ohms or less, it is recommended that an impedance matching transformer be used to transform the low impedance to a level where improved noise performance can be achieved. In this connection, noise figure contours are given for the basic amplifier when used in conjunction with the PAR Model AM-1 Input Transformer.

The noise contours were measured as follows:



A noise generator was used to provide a calibrated white noise source (equal power per cycle of bandwidth). The source impedance is determined by resistor R1 in series with the output resistance of the noise generator. The over-all noise output with the output of the noise generator reduced to zero (i.e., amplified Johnson noise) is first measured on the RMS voltmeter. The white noise signal from the generator is then applied to the amplifier under test, with the output signal of this unit being applied to a tuned amplifier which determines the noise bandwidth of the system. Since noise POWER adds directly and noise VOLTAGE adds vectorially (i.e., 1 mv of noise plus 1 mv of noise equals 1.414 mv of noise), the output of the noise generator is increased until the output as measured on the voltmeter is 1.4 times the value previously measured. The output of the noise generator is read from its front panel meter in microvolts/root cycle and, in this measurement technique, equals the total noise referred to amplifier's input.

The magnitude of the Johnson noise, which would be present even in the so-called "ideal" amplifier, is given by

$$e_n^2 = 4kTB_n R$$

where

e_n = rms noise voltage within bandwidth of measurements.

T = absolute temperature in degrees Kelvin.

k = Boltzmann's constant = 1.38×10^{-23} joules/degree Kelvin.

B_n = bandwidth over which the noise voltage is measured.

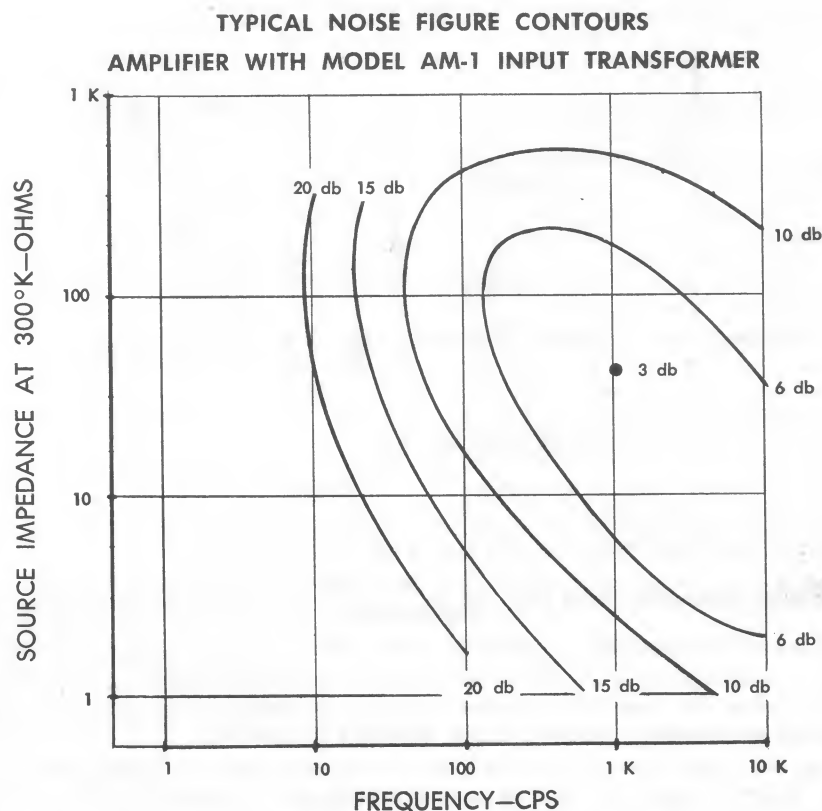
R = resistive component of impedance across which voltage is measured.

By comparing the above mentioned noise quantities in a variation of the above noise figure equation as follows:

$$F = 20 \log_{10} \frac{\text{TOTAL Amplifier Noise (i.e., Johnson Noise \& Noise Introduced by Unit)}}{\text{Calculated Johnson Noise}} \text{ DB}$$

the noise figure at a particular source impedance and center frequency is determined. By varying R1 while maintaining a fixed center frequency on the tuned amplifier, noise figure as a function of source impedance is determined. By changing the center frequency at which the tuned amplifier is set and maintaining a given source impedance, noise figure as a function of frequency is determined.

The contours shown represent the results of performing these measurements for a typical production CR-4 or CR-4A.



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